Range Commanders Council

OPTICAL SYSTEMS GROUP

DOCUMENT 463-08

STANDARD TESTING PROTOCOLS FOR HIGH-SPEED DIGITAL IMAGERS

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STANDARD TESTING PROTOCOLS FOR HIGH SPEED DIGITAL IMAGERS

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PREFACE

This document presents the results of actions by the Optical Systems Group (OSG) of the Range Commanders Council (RCC) under Task OS-29 to identify standardized testing methods for evaluating high-speed digital imagers. This document defines specific optical and electronic tests that can be performed to evaluate high-speed digital imagers, guidelines on how to perform the tests, and samples of actual test results. Although there are several good software applications available that incorporate ISO Test standards, the OSG Working Committee agrees that the Imatest™ software should be accepted by the RCC working groups as the testing standard. Imatest™ is a suite of programs for measuring the sharpness and image quality of lenses, digital cameras, digitized film images, and prints using inexpensive, widely available targets.

The RCC gives special acknowledgement for production of this document to:

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ACRONYMS

c/p	Cycles per pixel
CMOS	Complementary metal oxide semiconductor
cy/mm	Cycles per millimeter
DIC	Digital Imaging Committee
IRIG	Inter-range Instrumentation Group
ISO	International Organization for Standardization
LLC	Limited Liability Company
LP	Line pairs
LW	Line width
mm	millimeter
MTF	Modulation Transfer Function
NIST	National Institute of Standards and Technology
OL	Output level
OSG	Optical Systems Group
PH	Picture height
RCC	Range Commanders Council
S/N	Signal-to-noise-ratio
SFR	Spatial Frequency Response
SNR	Signal to noise ratio
U.S.	United States
USAF	United States Air Force

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CHAPTER 1

INTRODUCTION

1.1 Overview

High-speed digital imaging systems are becoming the dominant means of photographic data recording in private industry and on United States (U.S.) government test facilities. Current state-of-the-art, high resolution sensors are producing high quality images that rival, and in some cases, surpass film imagery. Media distribution to customers occurs now in a matter of hours compared to sometimes days for film-based systems. Conventional computer hard drives and displays are the only things needed to view test images. Desktop photogrammetric data reduction algorithms are available that eliminate painstaking procedures to extract image metrics. All of these improvements have had an impact on camera manufacturers to produce better imaging products for use on the test Ranges.

One of the primary challenges for users of high-speed imaging systems is to determine which system will best suit his needs. Camera performance specifications issued by manufacturers can be confusing and may not be based upon common performance standards. The scope of this task is to identify and recommend available electro-optical tests and procedures that comply with standards published by the International Organization for Standardization (ISO); these tests and procedures can be used to quantify camera performance and to make equitable comparisons from different manufacturers. A synopsis of each test is included along with references and links to detailed information about the standards. This document concentrates on the two most important system performance specifications:

a. Resolution, or image sharpness
b. Sensor sensitivity or ISO

1.2 Background

Over the past several years, all U. S. Government test facilities have been undergoing a methodical and purposeful transformation from the use of the older mechanical film-based optical data recording to electro-optical high-speed digital recording systems. High maintenance costs for the older camera systems, elimination of instrumentation film stocks, and environmental concerns over chemicals to process what film is available, have prompted industry to design and manufacture solid-state high-speed photographic instrumentation to replace legacy film systems.

Film cameras have several independent operational parameters that limit overall system recording performance. Contributing to the limits of what film systems can do include the following:

a. The mechanical drive mechanism that physically moves the film through the camera
b. The limiting film emulsion speed, grain and resolution
c. The physical size weight and power requirements

Designers of high-speed digital recording systems have been challenged to not only replicate film systems performance, they have also been challenged to improve performance over film systems. Complementary metal oxide semiconductor (CMOS) sensors that incorporate small, light sensitive pixels result in large area, high resolution imaging devices that rival the quality of instrumentation film emulsions. Images can be previewed prior to recording to ensure that lighting, contrast, focus, and timing are all acceptable for data reduction.

Rapid advances in high-speed digital imaging technology parallels the technology advances in the solid-state computer industry. This is not surprising due to increased requirements of imaging systems for data transfer speed and storage capacity. End users are requesting longer recording times for longer missions which require high data transfer rates to solid-state recording devices.

There is an increasing availability of high-speed digital imaging systems on the market today and all manufacturers are eager to emphasize the most outstanding operational specifications of their products. Sensor speed, sensor resolution, color reproduction, data download speed, timing accuracy, grayscale depth, and dynamic range are some of the more important performance specifications the end users use to evaluate systems in order to determine if any one specific imaging system will meet mission requirements.

One potential problem with using the manufacturer specification sheet is that there is no way for the end user to know exactly how that particular specification was measured. Companies may quote sensor resolution in number of pixels but may not directly correspond to a resulting quality image or edge sharpness. Camera sensor speeds or ISO specifications are quoted by manufacturers with little or no test verification to back up the numbers. Different cameras use different schemes to time stamp Inter-range Instrumentation Group (IRIG) on their images with no explanation of how the accuracies were actually measured.

Comparing performance specifications among camera systems using only manufacturers issued data without substantiating test reports could result in the end user choosing a system that may not be the best for meeting his test requirements. Having a program of standard testing protocols that can be used to accurately evaluate camera performance will allow users to verify or disprove manufacturers' claims and to objectively compare products of different manufacturers to one another.

Users of high-speed imaging systems can leverage upon standards that have been adopted to evaluate electronic still camera performance to verify operational specifications of their high-speed imagers. Well defined test procedures for measuring sensor sensitivity (ISO) and image sharpness using the Modulation Transfer Function (MTF) are presented here.

1.3 Existing Standards

The International Organization for Standardization (ISO) document number ISO 12233:2000 describes detailed testing methods to perform resolution measurements for digital still cameras (see Reference 5a). These resolution measurements can be made by analyzing images of targets on a specially designed test chart defined in the Standard. Visual resolution, limiting resolution, and spatial frequency response in terms of the MTF of the camera

lens, sensor, and in-camera imaging processing, are measurable. The test procedures presented in the ISO Standard uses a diagnostic algorithm to analyze digital image data of the specific slanted edge camera target.

The ISO 12232 describes detailed testing and analytical methods to determine the ISO speed rating for a camera sensor (Reference 5b). The test procedures presented in the Standard use a calibrated light source to calculate the illumination at the camera sensor plane and a computer diagnostic tool to calculate the speed ratio at two measured signal to noise ratios (SNR)s. The two SNRs of interest are SNR = 10 and SNR = 40.

1. There is no goal to include either of these ISO Standards in their entirety in the body of this document. The Standards can be purchased from several sources and the instructions for making the measurements are well written. There are also private companies that can evaluate camera systems based upon the measurement techniques discussed in the Standards.
2. The goal of this task is to identify available testing procedures and software applications that are compliant with ISO 12232 and 12233 that can readily be adopted by the user to thoroughly evaluate camera systems at the user's own facility.

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CHAPTER 2

TESTING METHODS

2.1 Resolution Testing

Image crispness, or sharpness, is a measure of image quality or how much object detail is transferred to the image by the camera sensor and lens. This measure is a very subjective of measure of perceived image quality since image sharpness is dependent upon viewing distance. A very large image with very low resolution, such as a billboard sign, when viewed from a long distance, can be perceived as sharp. The two primary contributors to image sharpness are edge acutance and spatial resolution. High edge acutance translates to rapid edge transition in the image or clearly defined borders and distinct boundaries between lighter and darker areas. Lower acutance results in grey or soft border areas when transitioning across an edge. One way to quantify edge acutance or sharpness is to use the rise distance of the edge transition. In the recommended test procedure the rise distance is the physical distance on the sensor in pixels or millimeters (mm) required to transition from 10 percent to 90 percent of the final pixel level.

The definition, or object detail, that is transferred to the image is defined by the spatial resolution of the image. Higher spatial resolution results in more image detail. This spatial resolution is determined by measuring how well the camera lens and sensor transfers a series of black and white bar targets of a certain density or frequency in object space into image space. The overall image quality and detail also depend upon how well the object space contrast is transferred into the image plane. A subjective concept such as image quality can be quantified by measuring how well a camera system transfers spatial detail and contrast from object space to image space. A "best" image is one with the greatest possible contrast and the highest spatial detail over the largest percent of the image plane.

2.1.1 Testing with bar charts. Historically, resolution tests have been conducted by photographing a standard bar chart such as the 1951 United States Air Force (USAF) chart or the newly designed targets in the ISO 12233 chart. Figure 2-1 illustrates the 1951 USAF chart and Figure 2-2 illustrates the newer ISO 12233 chart. The image would then scanned or printed on film and examined to determine the highest spatial frequency where image detail vanishes or where the highest spatial frequency where a discernable pattern is visible. Using these types of charts and then reproducing the image for visual examination is a very subjective method. This limiting spatial frequency usually occurs where the contrast is around 5 percent and does not generally represent usable images for photogrammetric data reduction.

A generally accepted level of image quality is where the modulation is 50 percent of the low frequency value or 50 percent of the peak modulation value where image detail is very good (Reference 5c).

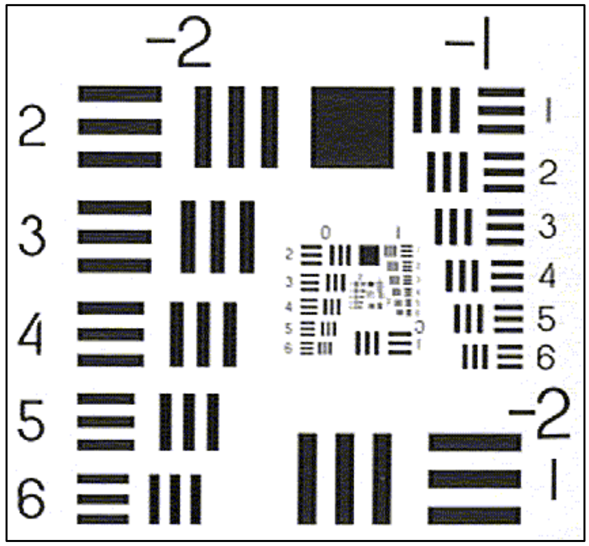

Figure 2-1. 1951 USAF test target.

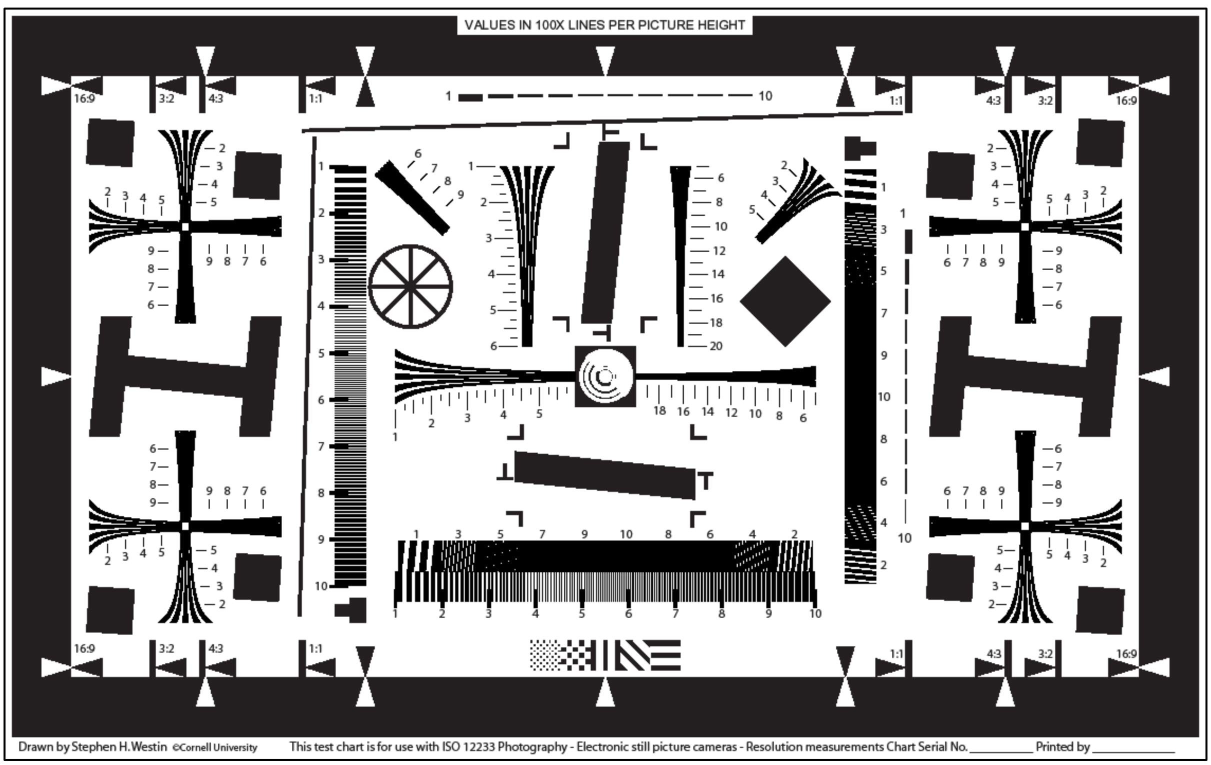

Figure 2-2. ISO 12233 Test resolution test target.

2.1.2 Testing With a Slant Edge. Instead of photographing a series of bar targets to determine the spatial frequency response of a system, a photograph of a slanted black/white edge can be analyzed to arrive at the Modulation Transfer Function (MTF) curve. According to Reference 5d,

> "The modulation transfer function is the Fourier transform of the impulse response. The impulse function is the response to a narrow line which in turn is the derivative of the edge response which is the intensity distribution in the image of an edge."

An image of a slant edge from the bar target is shown at Figure 2-3.

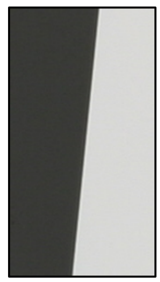

Figure 2-3. Image of a slant edge from a bar target.

The mathematical function that relates image contrast and spatial detail is the MTF or spatial frequency response. When the MTF is plotted, spatial frequency in line pairs per millimeter (lp/mm) or cycles/millimeter (cy/mm) are displayed on a logarithmetic (log) scale on the x-axis and the percent of contrast modulation is displayed on a log scale on the y-axis.

The ISO 12233 Standard describes in detail how the algorithm analyzes the edge image and calculates the derivative of the edge response to produce the spatial frequency response of the camera and lens. In practice, a single image of the black/white slant edge target is taken with the camera under test and a software application used as a plug-in module to an existing photo analysis program is utilized to analyze the edge in the image. One goal of preparing this document is to identify available applications that are based upon and are in compliance with the algorithms presented in ISO 12233.

2.2 Sensor Sensitivity Testing

Another important performance characteristic for a high-speed digital camera is the sensitivity of the camera sensor. This sensor sensitivity determines how well the camera performs in low light situations, with a fast shutter (short exposure) or behind long lenses with higher f/numbers. This sensitivity, or speed value, is a number calculated from an exposure at the sensor that produces a predefined signal output. The ISO Standard 12232 stipulates that a digital camera produce a specific signal-to-noise-ratio (SNR) as a result of a specific illumination on the sensor to achieve a certain ISO value.

The speed rating for a digital camera should be comparable to those defined by Standard ISO:5800:1987 which specifies how to calculate film speed (Reference 5e). The film speed is determined from a plot of optical density of the film (D) versus log of exposure in lux-seconds,

also known as the Hurter-Driffield or "D log E" curve. Figure 2-4 illustrates a representative characteristic curve for film. The regions of interest on the curve are:

a. The underexposed area or "base + fog"
b. The toe area
c. The linear region
d. The shoulder
e. The over exposed or saturation region

The minimum exposure (E_{min})is said to start at the point at which the density (D) rises to 0.1 above the base + fog level; the exposure (E) at which that occurs is the minimum exposure. Dividing that value into 0.8 gives the speed of the film.

$$S=0.8/E_{min} \quad \text{(Eq. 2-1)}$$

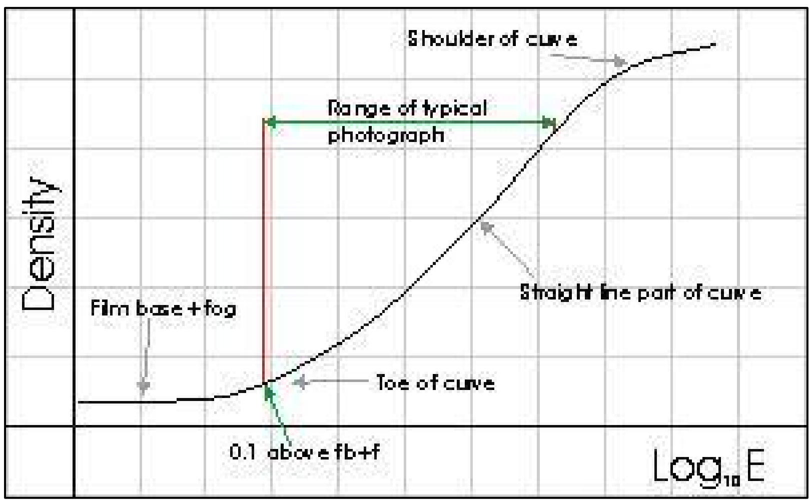

Figure 2-4. Representative characteristic curve for film.

This works for film because film is a threshold detector. In order to increase the sensitivity of film, designers must increase the grain size, but this reduces the system resolution performance. Solid-state sensors are linear detectors, so a camera manufacturer can always increase the gain of the system to obtain better signal. Unfortunately, this increase in system gain also increases the system noise, so this technique yields an improvement in paper specification but not in field performance. This is analogous to increasing gain size, but it is unlikely that a camera manufacturer would explicitly report the corresponding reduction in spatial resolution. These problems are mitigated by using the sensor's SNR as the reported metric.

The ISO Standard 12232 describes two methods of calculating sensor speed in detail: the saturation-based speed and the noise-based speed. Actually two ISO noise based ratings are recommended; one that corresponds to an exposure that produces a first "acceptable" image (SNR=10) and one that corresponds to an exposure that produces a first "excellent" image (SNR=40). The Standard defines the following:

$$S / N_x = \frac{H \cdot g(H)}{\sigma(D_H)} \qquad \text{(Eq. 2-2)}$$

Where:

S/Nx is 10 (corresponding to the first acceptable image) or 40 (corresponding to the first excellent image).

H is the photometric exposure, in lux-seconds. The source intensity must be known or measured by National Institute of Standards and Technology (NIST)-traceable means; it is combined with the exposure and f/# to calculate the focal plane exposure.

g(H) is the rate of change in the output level divided by the rate of change in the input level. This must be calculated from values in successive test frames.

$\sigma(D_H)$ is the standard deviation of the monochrome output level values taken from a standard (64 x 64) pixel area. This must be calculated from each test frame.

D_H is the monochrome output level.

A number of images captured over the entire luminance range of the sensor must be analyzed to determine the SNR for a camera sensor. A calibrated light source must be used so that the source intensity will be known. The light source may be used with an integrating sphere to produce a uniform light source. The intensity is typically varied with a variable aperture so that the lamp color temperature remains constant. In practice, the analysis of the images must be performed with third party software applications. It is one goal of this document to identify those applications that are based upon and in compliance with the analysis methods presented in the ISO 12232 Standard

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CHAPTER 3

COMPLIANT TEST PROCEDURES AND ANALYSIS TOOLS

After exhaustive surveys in the open literature and internet searches, the Range Commanders Council (RCC) digital imaging committee (DIC) identified one primary software application that is compliant with the existing ISO Standard for resolution testing. This application is the Imatest™ software package available through:

Imatest™, LLC
3478 16th Circle
Boulder, CO 80304
http://www.imatest.com/docs/contact.html

The Imatest™ software is not the only application for sensitivity measurement. The user must also have an integrating sphere and third party software for analysis. The sphere and software can be purchased as a unit or the user can purchase just the source and then download recommended analysis software.

3.1 Imatest™ Resolution Testing Application

The Imatest™ software application is available for purchase and download at **http://www.imatest.com/docs/contact.html.** The computer code that calculates the MTF/ Special Function Register (SFR) are from a Matlab program written by Mr. Peter Burns to provide the means to make the ISO Standard functional**.** The original Matlab code is available on the I3A tools download page (Reference 5f).

Many companies from several different optical industries have adopted Imatest™ as their standard testing protocol for resolution and MTF/SFR testing. This software application is a very powerful tool that provides a complete range of analysis programs for other image quality characteristics other than resolution.

There is no intent here to go into full discussion of the functionality of Imatest™. The software provides very detailed instructions for the user to measure system resolution and MTF. One brief example is presented here.

Figure 2-2 shows the full resolution test chart from ISO Standard 12232 documentation. A small area of one slant edge section is used to determine the SFR using the Imatest™ software. Figure 2-3 illustrates an enlarged region of interest of the slant edge that the analysis code uses to do the calculation. Figure 3-1 is an actual calculated MTF in line widths per mm.

There is a lot of information displayed from the Imatest™ test results (Figure 3-1). The first is the title of the file from the calculation, in this case "Sample image from high-speed camera." The left side of the upper chart denotes that a vertical edge was photographed to calculate a horizontal edge profile. The actual image height and width in pixels is given that was

used for the calculations along with the total number of pixels in the camera sensor. The default gamma of 0.5 is the estimate of camera gamma used to linearize the image.

The black text on the right side of the upper chart denotes the unsharpened 10 percent-90 percent edge rise distance in pixels as outlined in paragraph 2.1 (Resolution Testing).

The lower plot charts the spatial frequency response of the sensor and lens combination, normalized on the X axis versus line widths per picture height (LW/PH) on the Y axis.

Another important result also given on the right side of the MTF plot is the spatial frequency at the 50 percent modulation point. This 50 percent modulation relates back to perceived image sharpness. It is given in cycles per pixel (c/p) and LW/PH.

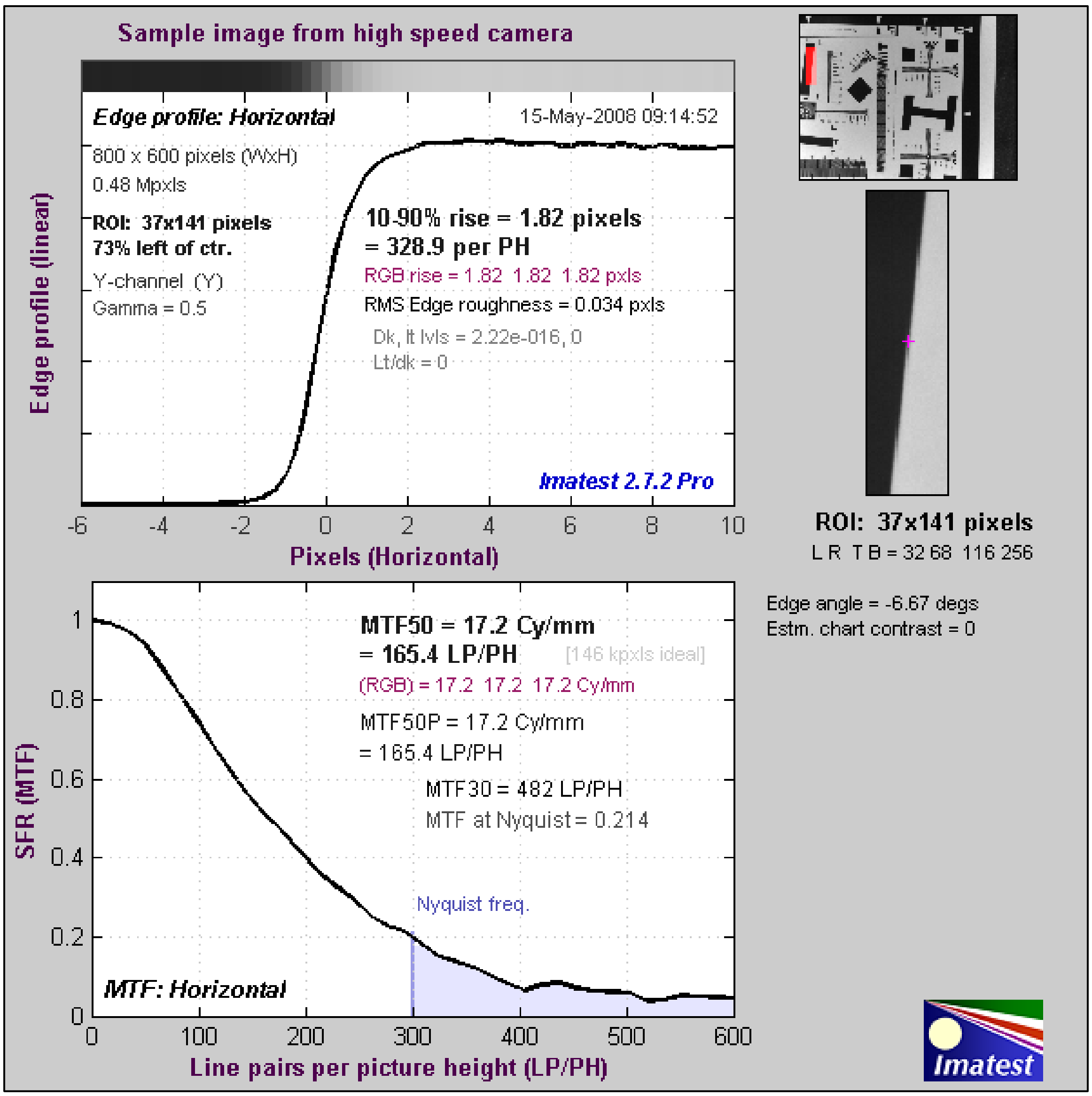

Figure 3-1. Imatest™ test results.

3.2 Sensitivity Testing Applications

Paragraph 2.2 stated that a calibrated light source is required to determine camera sensor sensitivity. The system should include an integrating sphere controller to vary the intensity so that measurements are repeatable and deterministic. The system should also include means to measure the intensity in photometric units (lux). In practice, the f/# and exposure are to be kept at the same level and the intensity is varied with the integrating sphere controller. The reported light intensities are to be recorded for each test.

Most of the camera interface software includes a tool for reporting the pixel gray scale values. For an 8-bit system, these will vary from 0 to 255. Because the S/N (i.e. SNR) is meaningless for 0 noise, images are not captured when the pixels show values of 0 or 255 since this means that the light has either not risen above the noise floor or that has risen above the saturation level. Effort to capture test images is concentrated near the noise floor end of the scale, as not all cameras are able to obtain S/N of 40 before going into saturation.

A software tool is recommended for measuring the signal (referred to in the ISO Standard as Output level or OL) and the noise (σ (D_H)). The measurements must be made on a square array of pixels, 64 on edge, or 4096 pixels. The output level is simply the average of the gray scale values in a monochrome system, or the weighted average in a color camera. The noise is the standard deviation of those 4096 points. Several image processing packages are capable of making these calculations. ImageJ, a Java-based software packaged developed by the National Institutes of Health (http://rsb.info.nih.gov/ij/), has been used for this purpose.

The final portion of the calculation requires the user to calculate the gain, g(H), from the above measurements and calculations. The exposures corresponding to S/N = 10 and S/N = 40 are unknown prior to the test, so it is unlikely the experimenter will actually capture test images corresponding to these values. Therefore, the corresponding exposure will have to be found by interpolation. Testing and measurement done at White Sands Missile Range completed the last step to this process using custom Excel spreadsheets. The process is that inputs to the spreadsheet include the measured light level, f/#, and exposure level, all of which are combined to yield the exposure (lux-seconds). The output levels and standard deviations are used to find the gain and S/N. The S/N is plotted against exposure on a log-linear graph (S/N is linear, exposure is logarithmic, typically encompassing the range from 10^{-4} to 10^{0} but adjusted as necessary).

The calculations to be used are explicitly written out in ISO 12232. The focal plane exposure (H) in Lux-seconds is given by Equation 3-1, which is derived from basic principles of radiometry (see, for example, Reference 5g).

$$H = T_{Lens} * \cos^4(\theta) * \pi/4 * (L * t)/A^2 + H_{Flare} \qquad \text{(Eq. 3-1)}$$

When assumptions are made about T_{Lens}, theta, and flare values, Equation 3-1 reduces to:

$$H = .65 * (L * t)/(A^2) \qquad \text{(Eq. 3-2)}$$

For Equation 3-1 and Equation 3-2, the following applies:

H	is the focal plane exposure in Lux-seconds.
T_{Lens}	is lens transmission.
L	is brightness in candelas per square meter, measured from the integrating sphere source.
t	is the integration time.
A	is the f/#.
θ	is the off-axis angle to the source.
H_{Flare}	is the contribution to H from lens flare.

The incremental gain is described as follows in the ISO Standard:

> "Determine the incremental gain of the system at each exposure, g(Hj), by averaging the change in output level divided by the change in exposure when going from the exposure immediately below the exposure to it, with the change in output level divided by the change in exposure when going from the exposure to exposure immediately above it."

This (incremental gain) relationship is given by:

$$g(H_j) = OL(H_j) - OL(H_j - \delta H_{i,j}) / 2\delta H_{i,j} + OL(H_j) + \delta H_{j,k} - OL(H_j) / 2\delta H_{j,k} \qquad \text{(Eq. 3-3)}$$

Where

H_i, H_j, and H_k	are the exposures of the previous, current, and next frame, respectively
$OL(H_x)$	is the output level corresponding to H_x (average grey scale value for the 64 x 64 block)
$\delta H_{i,j}$	is the change in exposure between H_j and H_i

Finally, the sensor speed at any one S/N value is calculated from equation 7 in the ISO Standard as:

$$ISO_x = 10/H_{s/n(x)} \qquad \text{(Eq. 3-4)}$$

CHAPTER 4

CONCLUSION

The objective of the Range Commanders Council (RCC) task which resulted in the production of this document was to identify optical test procedures that could be performed by the end user to quantify two of the primary high-speed imager characteristics of resolution and sensitivity. The requirement was that the tests be based upon and be compliant with accepted standards for resolution (ISO 12233) and sensitivity (ISO 12232). Goals were that the test procedures would be straightforward, could be done in a timely manner at a user's facility to verify manufacturers' claims, and could quantify imager performance under certain lighting conditions and with different optics on the cameras.

Thorough technical surveys of publications, journals, open literature, and Internet sites were performed.

The most thorough and technically sound application for the resolution testing was the Imatest™ software available through:

Imatest™, LLC
3478 16th Circle
Boulder, CO 80304
http://www.imatest.com/docs/contact.html.

The Imatest™ software is well documented and is straightforward to run on any user computer. Using this software, an image of a standard test chart can be analyzed and a resulting graph of the Modulation Transfer Function (MTF) can be printed. The image processing software automatically accomplishes measurements. The software not only measures the spatial frequency response, it measures other imager characteristics as well. The RCC Optical Systems Group (OSG) recommends that the Imatest™ software be the testing application of choice for resolution measurement.

An alternative to purchasing the Imatest software and performing the testing in house is to task a commercial testing laboratory to evaluate camera performance. Outsourcing this service does have the advantage that the user does not have to dedicate laboratory testing space, computing power and personnel to perform the analysis. Several optical companies that have expertise in optical manufacturing and testing were identified during the completion of this task.

Optikos Corporation is one company that manufactures equipment for the measurement of optical image quality. The company provides product testing services that can evaluate high speed digital imager performance. Optikos is located in Wakefield, MA. The web address is www.optikos.com.

Another facility that was identified was Optical Testing Laboratory in Corvallis, OR. They provide image quality evaluation for optical systems and information technology systems. Their contact information is http://www.opticaltesting.com/Contact.htm

Another option for the user (instead of using the Imatest software and printing the embedded test charts) is to purchase pre-printed resolutions test charts and down load third party MTF testing algorithms. This option may be less expensive in the long run, and purchasing commercially printed test charts guarantees good grey scale and dynamic range.

Another version of the MTF analysis software can be obtained from MITRE Corporation at http://www.mitre.org/tech/mtf/.

MITRE has an application to compute the MTF using a sine wave target or the contrast Transfer Function using a printed bar target. They also have modified existing algorithms to compute the spatial frequency response using an edge target.

A source to purchase the pre-printed resolution targets and charts is Sine Patters LLC in Pittsford, NY. Their contact information is http://www.photonicsonline.com/storefronts/sine.html.

The method for determining high-speed imager sensor sensitivity did not result in such a straightforward solution. This measurement requires the user have a controllable standard light source to calculate the incident radiation on the sensor by knowing the camera exposure and lens f/#. A series of images recorded at increasing exposure levels must be evaluated to measure the output level of and to calculate the sensor gain with expressions given in paragraph 3.2. The exposure levels where S/N = 10 and S/N = 40 are the two primary points of interest. The ISO of the sensor can then be calculated at these two levels.
If the user chooses to purchase an integrating sphere and control system to evaluate sensor sensitivity in house, one source is Labsphere, Inc., in North Sutton, New Hampshire. Their web contact information is http://www.labsphere.com/services.aspx#calibration.

The user can also outsource the task of evaluating sensor sensitivity just as in the case of MTF measurement. This does save the initial investment of purchasing the integrating sphere and control systems. One good source for having the camera sensor evaluated is Electro Optical Industries, Inc., in Santa Barbara, CA. Their contact information is http://www.electro-optical.com/html/

Users of high-speed imaging systems have several options to evaluate imager performance using the recommended test procedures for sensitivity and resolution or to out source the evaluation to commercial testing facilities

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